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THE BIS TELESCOPE
A Proposal for a Telescope Mirror To Be Built in Space

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A proposal for a telescope mirror to be built in space

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(Abstract)

The conventional technique for producing a perfect paraboloidal surface by rotating a bucket of fluid is introduced as the "simple model," which becomes the standard of reference by which other dynamical methods for forming parabolic mirrors may be judged. Departures from this model are known as perturbations of the simple model.

An abbreviated history is presented of several highlights in the formation of liquid parabolic mirrors: E. Borra and coworkers on liquid mercury mirrors; R. Angel et al., on large, stiff, honeycomb paraboloids of borosilicate glass; and the European Southern Observatory's (ESO) effort on lightweight, thin, low-expansion glass mirrors with actively controlled figures.

The general perturbations from the simple model, inherent in the spin-casting of large paraboloids on the Earth's surface, are considered, couched in terms of a nominal mirror model of 20-m aperture and f/1 focal ratio.

A logical extension of the mirror spun-cast on the Earth's surface is then presented: i.e., a dynamical analogue, spun-cast in space. The space-spun system, accelerated by tether restraint, introduces additional perturbations from the simple model. The nature of these

perturbations is discussed in terms of the nominal 20-m mirror for tether restraints of both 1 and 10 g's. Limited by the confines of this general overview, a favorable case is made for truly large telescope mirrors to be built in space (BIS) as the "wave of the future." The paper concludes with a proposal for a 2-m mirror to be studied by computer modeling and, perhaps, to be spun-cast in space to validate the technique.

1. INTRODUCTION

It is well known that the surface of a fluid in a bucket becomes a paraboloid of revolution when the bucket revolves at constant angular velocity about an axis fixed in an inertial frame and which is coincident with a constant, parallel field of force. This is referred to later as the simple model.

The liquid parabolic mirror is a surprisingly old concept, as revealed by Ermanno Borra et al., having been proposed on more than one occasion over the last two centuries [1]. In fact, the simple model may be as old as the invention of the calculus [2]. The physicist R.W. Wood—in 1908—appears to have been the first to achieve fair success with this concept [3]. He spun a 20-inch pan of mercury, mounted on a vibrationally "isolated" turntable, which in turn was set up on a heavy concrete structure at the bottom of a well. The turntable was spun through a homemade "magnetic clutch" by a motor in an adjacent well. The focal length could be varied by controlling the angular velocity. Subsequently, an optical flat was used to deflect the moon's image into the well and, after great care in the centering and alignment of the rotation axis along the vertical, a good, stable image was achieved, somewhat marred by slight vibrations of the turntable and by variations of its rotation rate. In a presage of future needs, Wood hoped to find a suitable material which could be spun in a fluid state and allowed to solidify, forming a parabolic mirror. He also suggested a nearly parabolic bottom to save mercury.

R.A. Schorn has examined the same concept with reference to the greater possibilities made feasible by new technology [4]. In particular, he reviewed recent progress with liquid mercury mirrors made by Ermanno Borra and his associates at the Université de Laval, Quebec, Canada [5]. Relatively cheap, high-quality liquid-mirror telescopes could be used as zenith transit telescopes. By some sacrifice of off-axis image quality (coma), together with a modified charge coupled device (CCD) readout, one might "track" a small region in declination and hour angle about the zenith. Thus, a "picket fence" of relatively inexpensive transit instruments might play a role in the frequent monitoring of a band in the night sky.

The most recent case for the very large liquid (mercury) mirror zenith-transit telescopes is ably stated by Borra and his collaborators [1,6]. They achieved several surprising experimental results and conclusions. The first was that the mirror spin-axis alignment was not too critical. For their 1.65-m mirror, diaphragmed to 40 cm, tilting the mirror by as much as 20 arc seconds produced no observable change in the parabolic figure as seen in the knife-edge test. They found that the images moved by twice that amount while remaining sharp and unaltered; thus, for small tilts, the central part of a liquid mirror behaved as if it were solid. They presumed the same behavior for the edges [6]. In the same reference, they performed an inadvertent but significant experiment. The mirror container, which was unstably supported, underwent a clearly discernible wobble with an amplitude of several arc seconds and an alteration to the mirror's spin period. To their surprise, the results of the knife-edge test and imagery remained stable. After some consideration of mechanisms, they concluded that this effect would permit the use of relatively low-quality bearings, with a concomitant and substantial saving in cost. They also found, as expected, that concentric, mirror-centered stationary waves, excited by vibrations from external sources, were effectively damped by the application of a high-viscosity surface layer (glycerin). They proposed mirrors as large as 30 m. The experience gained helps in the understanding of the limitations to the whole spun-cast mirror concept. However, should the mirror space-manufacturing techniques that are outlined below prove feasible, then the astronomical impact of this ingenious adaptation of the liquid mercury mirror, with all its inherent limitations (tracking), remains in doubt. The same point might be extended to all large Earth-bound telescopes.

Since 1985, Roger Angel, at the University of Arizona, has been spinning a large oven of molten glass on a massive turnable [7,8]. He has produced low f/ratio paraboloids from much less glass. This cuts both cost and time because, in the limit, it requires only half the glass, one-fourth the annealing time, and very much shorter grinding and polishing stages. For example, a conventional 8-m blank of borosilicate (Pyrex) glass having an aspect ratio (diameter/thickness) of 8:1 would weigh about 280 000 pounds (127 000 kg) and would require 6 months to anneal. The corresponding figures for an 8-m mirror, spun-cast from glass chunks and of unit focal ratio [aperture/(focal length)], are about 210 000 pounds (95 254 kg) and 6 weeks. In addition, the approximately 70 000 pounds (31 751 kg) of glass that would have to be rough-ground from the 280 000-pound blank to produce the paraboloidal surface has already been removed by spin-casting. Finally, a further reduction of the mirror weight and annealing time can be obtained with an oven which has either a thin concave or a hexagonal honeycomb-ribbed mold. Each technique has both distinct and shared advantages and some disadvantages. The experiments by Angel explored the latter technique which, along with simplicity, promises to deliver relatively stiff, lightweight, thermally responsive mirrors.

By August 1988, Angel's group had delivered a 3.5-m borosilicate honeycomb paraboloid to the Astrophysical Research Consortium (ARC) for grinding and polishing. Upon completion of a second 3.5-m mirror, the same group will attempt one of 6.5 m. Success here will be a milestone enroute to an 8-m mirror [9].

The European Southern Observatory (ESO) favors the thin, curved-back mirror, which must be actively supported at many (150) points, as primaries for its array of four independent 8-m telescopes known as the Very Large Telescope (VLT) [10]. Each 8-m primary will be a mere 20 cm thick (an aspect ratio of 40:1) and will weigh about 24 tons. When used collectively, the array will have a light-gathering power equivalent to a monolithic 16-m mirror. The first telescope is targeted for completion by 1994 and the entire project by 1998, at a site in northern Chile, and at an estimated cost of $250 million.

2. GLASS MIRROR SPUN-CAST ON EARTH

Neglecting the problems of angular velocity control and vibration of the oven, the spin-casting technique succeeds only to the extent that the local g-field "appears" to be both constant and parallel. Viscosity also plays a considerable role for spun glass mirrors. For easy visualization, consider the following nominal model: a 20-m-aperture mirror of unit focal ratio or f/ratio. A 20-m-aperture, f/1 mirror has by definition a focal length equal to 20 m.

2.1 Deviation from Strict Parallelism

On the surface of the Earth, the maximum deviation of the local g-field from strict parallelism (convergence angle), over a 20-m mirror, is about 0.32 arc seconds. While strictly central, it may be considered a parallel field. As pointed out by Borra et al., such large mirrors are governed by geometrical optics; the critical parameter is the departure of the slope (derivative) at each point of the nearly parabolic mirror from that of the paraboloid at the corresponding point, not the departure of one figure (function) from the other [1]. This differential slope can be exactly calculated for a central force field. For a distant force center (distant compared to the mirror aperture), its value varies linearly with radial distance from the bucket spin-axis and is just the parallax of the force center. Thus, the maximum differential slope of the 20-m mirror is about 0.32 arc seconds, corresponding to an image displacement of twice that amount. The effect is equivalent to a simple change of focus [1].

2.2 Kinematic Effects

Finally, on the surface of the Earth, there are two weak kinematic effects (perturbations from the simple model) which result from the fact that a coordinate system, fixed on a rotating Earth, deviates slightly from a strictly inertial frame. The maximum centripetal acceleration of the Earth's surface (i.e., the mirror coordinate frame) is a negligible 0.035% of gravity at the Earth's equator. The second perturbation is the fictitious (Coriolis) acceleration of each element of mirror fluid because of its motion (spin) in the rotating frame of the Earth. The required bucket (oven) rotational velocity for this f/1 mirror is about 5 rpm. This angular rate and mirror radius combine with the Earth's diurnal rotation to produce a maximum Coriolis acceleration which is a negligible 0.01% of the local g-field.

2.3 Summary for Earth-Spun Mirror

For a 20-m glass mirror, spun-cast on the surface of the Earth and rotating at several revolutions per minute, the Earth's huge scale and slow diurnal rotation make the local net (gravitational) field resemble a parallel and constant force field in an inertial frame. Thus, neglecting questions of the oven spin velocity control and vibration, the Earth-spun mirror is an excellent analogue of the simple model. However, because of the high viscosity of the mirror material, Earth-spun glass mirrors are not of highest optical quality and require grinding and polishing. If the g-field could be scaled up, say to 10 times gravity, such might not be the case.

3. GLASS MIRROR SPUN-CAST IN SPACE

In space there exists an exact, although inapplicable, analogue to the simple model. It is just the continuous, uniform, rectilinear acceleration of the mirror bucket along its spin-axis at 1 to 10 g's. This acceleration must be maintained over a hardening period, say 5 days. At only 1 g, the terminal velocity would be 1.4% of the velocity of light.

The space-spun mirror utilizes another approximation to the simple model which bears a superficial resemblance to the Earth-surface-spun mirror. In space, the local ("constant-parallel") g-field at the Earth's surface is replaced by a centripetal acceleration maintained by swinging a spinning bucket (oven) of fluid on a long tether, at constant angular velocity, about a distant center-of-mass. The bucket spin-axis is along the tether; the tether revolution axis is always normal to the tether and determines the pole of the bucket "orbital" plane (fig. 1).

4. MAJOR PERTURBATIONS OF THE SPACE-SPUN MIRROR

Now consider the previous mirror—a 20-m-aperture, f/1 mirror—as a space-formed mirror. Two cases for the same geometry will be examined. The tether length (center of mass to bucket) in both cases is 10 km, but the tether (centripetal) acceleration varies.

In the first case (**Case I**), the tether (centripetal) acceleration equals 1 g. As with the Earth-spun mirror, the bucket spin period is about 5 rpm. The bucket orbital period, about the center of mass, is 3-1/3 minutes.

This substitution of a rotational tether-restraint on the spinning bucket system for the ideal, but impossible, constant rectilinear acceleration makes a rough analogue of the simple model possible—at a price. The limitations of tether length and tensile-strength, together with the high angular velocities necessary for reasonable restraint accelerations, drive the unwanted kinematic effects, so small in the

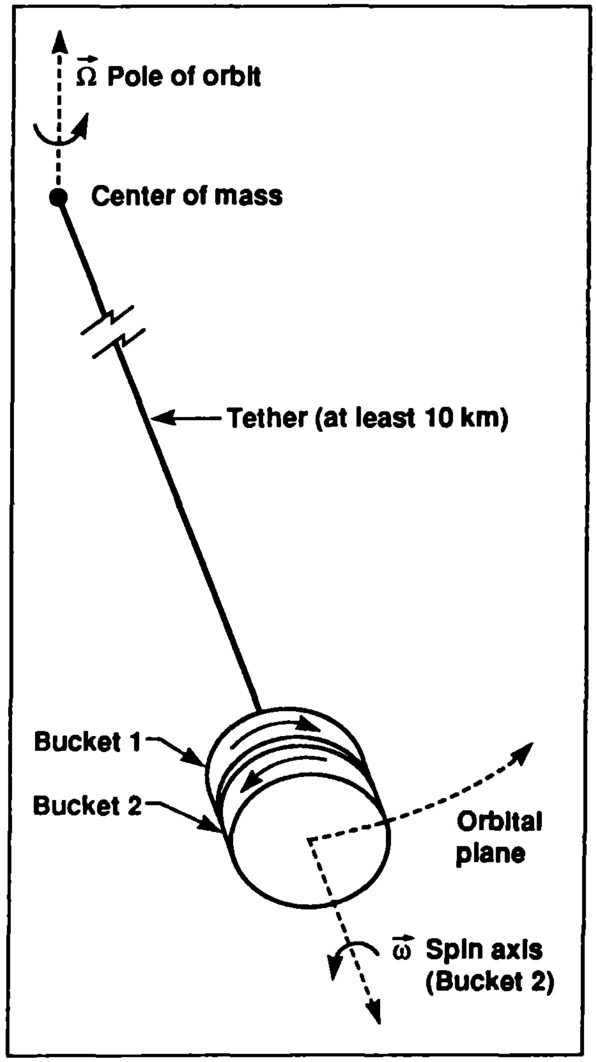

Fig. 1 Schematic of a space-spun mirror orbital system, with a pair of counter-rotating buckets. Ω = orbital angular velocity, and ω = spin angular velocity. (Not to scale.)

Earth-bound system, into the realm of perturbations which must be investigated.

4.1 Deviation from Strict Parallelism

For a 20-m mirror, the maximum deviation of the *g*-like tether acceleration from strict parallelism is now a much larger 206 arc seconds (the parallax of the center of mass). In the general case for the space-spun mirror, the tether restraining accelerations on mirror fluid elements are neither parallel nor central. These centripetal accelerations are always directed along the perpendicular from the individual fluid elements to the pole of the orbit. Consider the accelerations on fluid elements along a mirror diameter. When that diameter is normal to the bucket orbital plane, these accelerations are parallel and are coplanar. When that diameter lies in the orbit plane, these accelerations are central and coplanar (fig. 1). At any intermediate position, the accelerations are "skewed" and have no common plane. The effect of such a varying (time and "type") field cannot be accommodated in a simple analysis. A worst-case, but very unrealistic, treatment of this effect is the assumption of a steady state central acceleration on all mirror fluid elements. Such a perturbation would produce a maximum change of slope of 206 arc seconds (parallax of center of mass) from the equivalent parabolic mirror. The net effect is undoubtedly much smaller. In reality, the fluid elements on a mirror diameter experience a "skew" field fluctuating between the extremes, which are planar central and planar parallel, but which is heavily time-weighted towards the parallel field. Finally, it is likely that the observed insensitivity of the liquid mercury mirror to the alignment of its force field with the bucket spin-axis may come to the rescue of the space-spun glass mirror. A 20-arc-second displacement between a tether centripetal acceleration and the bucket spin-axis, for a 10-km tether, is 1 m or 10% of the maximum possible excursion.

4.2 Coriolis Acceleration

The 5 rpm angular rate and mirror radius combine with the bucket's orbital revolution of 3-1/3 minutes to produce a maximum Coriolis acceleration which is 3.2% of the *g*-like tether acceleration. The Coriolis acceleration, expressed as a triple vector product, resolves into components along the bucket spin-axis and along a bucket fluid element position vector. The space mirror tether geometry, in which the bucket orbital angular velocity is normal to the bucket spin-axis, forces the resolution into a single component along the tether (bucket spin-axis). This Coriolis effect, stationary in the rotating center-of-mass system, subjects the mirror fluid elements to a force which varies linearly with the distance from the bucket spin-axis (tether) and sinusoidally with the bucket spin period. Its direction is alternately parallel and antiparallel to the tether; i.e., it is always a contribution to the "parallel" field. Except for amplitude, it is equivalent to a spun mirror formed at the equator of the Earth. Its action on the bucket is that of a set of distributed symmetric couples where, in the spinning bucket system, it produces an alternating augmentation and diminution of the tether force over successive half periods. It is 90° out of phase with the central field phase of the "parallel" perturbation discussed in 4.1 above. Specifically, the Coriolis acceleration has its maximum absolute value when a fluid element lies on a mirror diameter normal to the bucket orbital plane; i.e., parallel to Ω, designating the pole of orbit (fig. 1). The value is zero when the fluid element passes through the orbital plane. The effect, relative to the tether g-like force, is that the "weights" of bucket fluid elements undergo periodic fluctuations over a maximum range of ±3.2% at the outer rim.

This "Coriolis" perturbation affects the spinning bucket (oven) in two ways.

First Effect of Coriolis Acceleration. There is an alternating "squish" of the molten mirror material from one side of the orbital plane to the other; i.e., from the currently "heavy" side of the mirror to the "light" side. This is best seen by again considering fluid elements along a mirror diameter. The Coriolis force on each of these elements is a sinusoidal force, normal to the mirror bottom, with an amplitude proportional to the radial displacement of the element and the period of the mirror. This forcing function tries to drive a standing wave in the mirror material (sloshing) with the same period, with a wavelength of twice the mirror diameter, and with a node at the mirror center. For a liquid of very low viscosity (e.g., mercury), the bucket spin frequency should be as far as possible from any natural resonant frequency of the bucket and mirror material. There should be no such problem with a highly viscous material like molten glass. In addition, the honeycomb-ribbed mold (baffles) and/or very thin fluid layer further enhance the viscous damping action in any mirror material.

Second Effect of Coriolis Acceleration. In a freely spinning bucket, such a set of symmetric distributed couples would produce a torque in the orbital plane which, combined with the bucket spin angular momentum, would maintain a direct or retrograde steady precession of the bucket spin axis. (It cannot produce a steady precession but can only maintain it if it already exists.) The response is more complicated here because this "tipping" torque is compounded with a torque produced by the tether tensile (*g*-like) restraint.

4.3 Tether-Induced Precessional Torque of a Single Bucket

The requirement that the bucket spin axis always be aligned along the tether forces the bucket spin axis to make one revolution about the center of mass once each bucket orbital period. The tether accomplishes this by rotating the bucket spin axis in the orbital plane, producing a torque normal to this plane. Such a torque, in concert with the bucket spin angular momentum, would maintain a freely spinning bucket in a steady precession normal to the plane of the orbit, if that precession already exists, but cannot initiate this precession. Again, the true response is more complicated because this precessional torque is compounded with the tether tensile restraint. Since the orbital angular momentum is only 1000 times larger than the bucket rotational momentum, this is not a negligible effect.

5. CONSERVATION OF ANGULAR MOMENTUM

The torques required by the simple single-bucket space model described above cause two of the perturbations from the simple model.

The first perturbation-causing torque is in the orbital plane (the Coriolis acceleration of the spinning off-axis bucket structure which produces a "tipping" of the mirror about the orbital plane)—i.e., the second effect of Coriolis acceleration described above. (Note: Although not a practical solution, in principle—for any geometry and a very special set of rotation rates—it is possible for a single bucket mirror to have the required orbital plane precession, maintained by the above Coriolis torque, which will just satisfy the required tether alignment described next, although this is neither a stable nor a desirable solution to these problems.)

The second perturbation-causing torque is normal to the orbital plane (bucket spin axis always aligned along the tether)—i.e, the tether restraint precessional torque described in 4.3 above.

Both of these perturbations arise because the angular momentum of the spinning bucket is not conserved. (Torquing a nonspinning bucket poses no problems.) Fortunately, there is an easy remedy. By simultaneously forming identical pairs of mirrors in radially adjacent, counter-rotating ovens (as shown in fig. 1), the total bucket spin angular momentum is zero, and the necessary torques produce no unwanted side effects.

6. NEGLECTED PERTURBATIONS

There are other perturbations of the space-based system not addressed here because they should be of lower order; i.e., tidal stresses in the mirror itself—some 20 orders of magnitude below the tether restraint acceleration—and radial oscillations in the tether. The tether oscillations are a small unknown quantity. This is not a "spring" system with the usual restoring force. There is no restoring force per se; the entire space center-of-mass system, including the bucket, is in orbit about the Earth. Short-period tether oscillations ("twanging") can be effectively damped and can, moreover, be easily incorporated into a computer-modeled study of the system.

Perturbation is a term which has been loosely applied. In this paper it has one of two interpretations: either it refers to a difference in some particular acceleration between that experienced by a fluid element of the simple model and its corresponding element of the space-spun orbiting system, or it refers to the time-integrated effects of such an "anomalous" differential acceleration. The appropriate interpretation is clear from context. In light of the above, the remaining perturbations from the simple model are of two types: (1) gravity gradient perturbations, and (2) non-inertial motion of the center of mass.

6.1 Gravity Gradient Perturbations

These arise from a nonuniform force field acting on an extended system. The entire center-of-mass, space-spun system is an extended one in the neighborhood of the Earth. This gives rise to a differential attraction between the Earth for the bucket and for the remaining mass of the system, the so-called gravity gradient forces. These "tidal" forces are transmitted to the bucket through the tether, as is the centripetal (tensile) tether restraint between the bucket and the center of mass.

6.2 Non-Inertial Motion of the Center-of-Mass

In the simple model, the rotating bucket system with constant, parallel, external force field is embedded in an inertial frame or, equivalently, the spinning bucket undergoes a uniform rectilinear acceleration along the bucket spin axis. The entire center-of-mass space mirror system is not an inertial frame but, neglecting other bodies, is one accelerated nonuniformly in its orbital motion about the center of the Earth. However, all such effects can be rendered insignificant by various devices; e.g., by "firing" the entire system into an elliptical geocentric "construction" orbit whose plane is normal to the bucket orbital plane about the center of. mass. The period of the construction orbit should be greater than the hardening time. The hardening time is the period required for sufficient cooling of the mirror so that it can retain its parabolic figure against all stresses.

6.3 Discussion of Case II

In the second case to be examined (**Case II**), the tether (centripetal) acceleration equals 10 g. In this case, the bucket spin period is about 15 rpm, and the bucket orbital period is 63.5 seconds.

Consider an ng tether with a fixed geometry and mirror figure (f/ratio). In a simplified analysis, the ratio of the Coriolis acceleration to the tether restraint acceleration is proportional to the ratio of the bucket spin angular velocity to the bucket orbital angular velocity. This ratio must be invariant if the f/ratio is to be preserved. Thus the relative Coriolis perturbation is the same as for Case I for all values of n. While the ratio of the Coriolis to tether accelerations is preserved, the torques are not, but we can eliminate their precessions by the mirror "pair-production" technique. To reduce the perturbations themselves, we can do any or all of the following: reduce the mirror aperture, increase the tether length, and/or increase the focal ratio.

The point to be made is that once a particular geometry (tether length and mirror specification) is adopted, the relative magnitudes of the perturbations are frozen, but their periods are not. Neither is the ratio of the tether g-like force to the viscous-creep forces. For a given geometry, the former is controlled by the square of the orbital angular velocity. Increasing the tether force, relative to the molten glass viscous forces, will enhance the mirror quality by making the mirror figure more responsive to the larger time-averaged forces—unlike the Earth-based system where the g-force is just the force of gravity. At the same time, the compensatory increase in the bucket spin velocity, necessary to preserve the mirror f/ratio, should diminish the effects of the perturbations by integrating out their rapid oscillations over a period, shorter yet by comparison with the characteristic viscous-creep response time. At first sight, higher tether forces appear to buy higher optical quality, a conjecture that can be answered by computer modeling which incorporates the rheological properties of glass, or perhaps by limited, small-scale tests in space. If this conjecture proves true, the exploitation of higher tether forces is an advantage of the space-based system, with no earthly analogue.

7. ADDITIONAL COMMENTS ON HIGH-g TETHERS

Although unconfirmed by computer simulation for a glass mirror spun-cast in space, one expects better mirror figures from higher-g tethers. The price to be paid for increasing the g-loading is that the tether mass becomes a larger fraction of the total mass to be orbited. The total mass includes the tether mass plus that of the loaded buckets (end mass). Rather than adopt a tether of standard cross section, one can calculate the constant cross section—and hence the mass—of an ng tether of length L, required to support an adopted end mass m_e.

As pointed out by one reviewer, such a 10-km tether, sustaining 10 g's at its extremity, will be about three times the adopted end mass. This reviewer believes that the advantages of spin-casting in space will only appear for tether restraints of 10 g's or so. He also thinks that the high freight costs to space for such a high-g tether will detract from the appeal of the concept.

The author's results for an ng, Kevlar 149, 10-km tether of constant cross section are, for several values of n, as follows:

$n = 1,\ m_t = 0.17\ m_e$

$n = 5,\ m_t = 1.05\ m_e$

$n = 10, m_t = 2.86\ m_e$

where m_t is the tether mass and m_e is the end mass (buckets plus mirrors).

Returning to the reviewer's second point: although it appears that high-*g* space-spun systems would be preferable, except for freight costs, it does not necessarily follow that lower-*g* systems have little merit. Suppose a mirror of 20-m or larger aperture could be spun-cast on the Earth's surface (1 *g*), then ground and polished to a good figure. Would this be of much value? Not on the surface of the Earth, where the problems of seeing, mechanical support, and housing for such a huge system would seriously degrade its value. Only if used in space would such a large mirror really come into its own. However, the cargo bay diameter required to transport such a large mirror into space will not become available in the foreseeable future. The point is that even a 1 *g* tether might prove useful if the grinding and polishing could be done in space, and there seems to be no inherent reason why they cannot.

A final point concerns the high-*g* tether. In a space-spun tether system, each element of the tether has only to sustain the orbital weight of the end mass plus that of the intervening tether; i.e., the weight of all exterior parts. On the other hand, since all tether elements revolve at a constant angular velocity about the CM, each contributes to the tether tension proportionally to its distance from the CM. This suggests the use of a tapered tether. The inner elements, which support most of the orbital weight but contribute least to it, should be of larger cross section than the outer elements, which support less of the orbital weight but contribute most to it. A tether of continuous taper is impractical, but a segmented tether, with each segment having a distinct but constant cross section, is feasible. For such an ng segmented tether, one can write a relation for the tether tension of the i^{th} segment and cross section in terms of the tension for the $(i + 1)^{st}$ segment. This system can be recursively solved, in terms of the end mass, from the outermost segment inward. For example, for a 10-km, 10 g tether comprised of 1-km segments, one finds:

$n = 10$, $m_t = 2.1\ m_e$, which is $<2.9\ m_e$ for the constant cross section tether.

The innermost 1-km segment has 1.4 times the cross section, and hence 1.4 times the mass, of the outermost 1-km segment.

8. SUMMARY FOR GLASS MIRROR, SPUN-CAST IN SPACE

The tether-produced g-like field for a 20-m space-spun mirror has significant perturbations from the simple model. These arise because the space system is an accelerated (rotating) reference frame. Since the tether length will always be small compared to the Earth's radius and the bucket orbital period short relative to the Earth's day, it will never closely resemble an inertial reference frame. However, since the g-like acceleration of the tether restraint can be scaled up, relative to the viscous forces of a molten mirror, and since the perturbation period can be made very short, relative to a characteristic viscous-creep response time, it is possible that the "averaging out" of these periodic perturbations over a bucket spin period will mitigate their effects sufficiently so that an acceptable mirror figure is produced. There is an irony here. If, ultimately, this technique is successful in space, its success will depend on the viscosity of the mirror material—the very reason mirrors of glass, spun on Earth, are not paraboloids of optical quality. On Earth, mercury mirrors are "perfect"; glass ones are not. In space, mercury mirrors may never be perfect because they track the perturbations; spun-cast glass mirrors, on the other hand, may prove to be fairly good. Only computer simulation or trial will tell, although a viscous phase lag is an essential ingredient for the success of a space-based system.

Because an Earth-based system closely resembles an inertial reference frame, while a space-based system does not, these techniques bear only superficial resemblance to one another. They both spin mirrors; that is the extent of the resemblance. Whether or not such a space-spun mirror is feasible can be answered by a careful computer-modeled study of the viscous fluid flow equations of motion, subject to the forces and boundary conditions which have been sketched. Such a study should make it possible to isolate a configuration space for success, if one exists, among the regime of parameters:

- Tether length and orbital angular velocity (which implies tether acceleration).
- Mirror aperture, f/ratio, and spin angular velocity.
- Mirror material viscosity.
- Total mass of mirror material, plus bucket (which, with mass of tether and tether acceleration, imply tether tensile force.)

Omission of tether tensile strength as a dimension of the success configuration space is not an oversight. Requisite tether tensions can be met in many ways: e.g., multiple tethers (cables), various cable diameters and materials, etc. So, from the total "success volume," a subset can be chosen that can be satisfied by some realistic tether geometric structure.

It should not be assumed that the success of the Earth-based spun mirror technique implies success for the space-based system. Nothing could be further from the truth. Certainly, a carefully considered analysis cannot dismiss the study of this space-based spun glass mirror production technique simply because it is already being done on Earth. It is not.

A "real" case may be selected to obtain a feeling for the masses and forces involved—namely, a 1/10th-scale (2-m) mirror on a 10-km tether. All the geometry requires is that a center of mass (CM) be established in space, by whatever means, around which a pair of 2-m "ovens," counter-rotating about the tether axis, are whirled. The CM can be set up in a variety of ways. One way is to have a 20-km tether separating two identical pairs of counter-rotating buckets ("ovens"). This is not a bad choice if a total weight (mass) to orbit is used as an overall measure of efficiency. Mass dispersal is the key; if the shortest tether (10 km) is required, it is necessary to anchor the tether in an asteroid (infinite mass). The following proposal, illustrating the above case, provides some order-of-magnitude mass estimates.

9. PROPOSAL FOR A 2-M (1/10th-SCALE) MIRROR

This proposal illustrates one particular geometry for the simultaneous space manufacture of as many as four test spun-cast mirrors at 1/10th scale. The nominal plan is for two sets of two coupled counter-rotating buckets (ovens), separated by a 20-km tether; for this example, assume a tether made of DuPont KEVLAR 149. (The relevant physical properties of KEVLAR 149 appear in Ref. 11.) At least one of the four buckets (ovens) is active; any, or all, of the others could be dummies with the appropriate weight distributions required to establish the center of mass. Dummy pairs would not have to be spun. If this or a similar program reaches the "engineering" phase, those physical properties of the tether material characterizing its reaction to a space environment (temperature, vacuum, and radiation) will also play a dominant role in its selection.

The following description contains both metric and English units, with one force-pound equal to 4.44822 Newtons and one kilogram equal to 2.2046 mass-pounds.

A KEVLAR 149 tether of 1-square-inch cross section (6.4516 cm^2) can, with a safety factor of two, support a tensile force of 250 000 force-pounds (1 112 000 Newtons). With a density of 0.636 pounds per linear foot, a 10 km by 1 square inch tether has a mass of 20 866 pounds (9464.8 kg or 9.4648 metric tons). The total mass for a 20 km by 1 square inch tether, to be transported to orbit, is 41 732 pounds (18 930 kg or 18.9 metric tons).

A 2-m blank of 10-cm thickness (aspect ratio = 20:1), with a specific gravity of 2.5, has a mass of 1730 pounds. A 2-m, f/2 paraboloid (depth of 6.25 cm, with minimum thickness of 3.75 cm) has a mass of 1190 pounds. With a honeycomb-ribbed-back mirror, the mass is probably well below the adopted mass of 1000 pounds (454 kg). The total adopted mass for four mirrors, or equivalent dummies, to be transported into orbit is thus 4000 pounds (1815 kg). Assuming that each oven is 10 times the mirror mass, the total oven mass-to-orbit is about 40 000 pounds (18 150 kg). This high estimate of some 86 000 pounds to orbit is roughly 1.5 shuttle loads and includes such ancillary equipment as power supplies, sensors, and control mechanisms. A modular tether construction can be anticipated, to be assembled from 1-km lengths of 950 kg/km, with each km on a 3-m-diameter, 3-m-long spool (about 100 turns per spool). The 1-km sections, equipped with "hooks and eyes" are easily coupled by astronauts. The tether may have a thin metallic (aluminum?) coat for protection against solar ultraviolet and the vacuum of space. One can imagine these 1-km, 1-ton sections as background cargo for every unfilled shuttle manifest. They are transported to orbit, joined with the previous cache, and perhaps stored.

The "weight in space" of the deployed, whirling orbital system for the 1 g total tether must also be considered. The tether tension consists of two parts: the integrated "weight" of the tether over its entire 10-km length, and the weight of mirrors and ovens, all in a 1 g field. Since the centripetal (restraining) tension varies linearly with radius for constant orbital angular velocity, the tether "space weight" is exactly one half of its value at 1 g, namely 10 433 force-pounds (4732 kg or 4.73 metric tons). The space weight of the mirror-oven combination is just the weight of a coupled pair: 2000 + 20 000 = 22 000 force-pounds (97 860 Newtons). So the total tether tension is just 32 433 force-pounds (144 300 Newtons).

The corresponding tether tensions (total space weights) for 5 g and 10 g tethers are about 162 200 and 324 300 force-pounds (722 000 and 1 443 000 Newtons) respectively. Computer simulations of this proposed model, over this range of tethers, are significant.

Although deployed by the space shuttle, the system is completely autonomous in operation. Short-term stability of the bucket spin period, less than one revolution, is passive. It relies on the stability of the bucket's spin-axis moment of inertia. The long-term stability, greater than one period, could be mechanically tuned by vernier control of this moment of inertia. At present the spin-period sensing mechanism is in doubt.

The rapidly changing bucket spin equator makes sidereal sensing difficult. The bucket spin period could be sensed by timing successive "transits" of a selected stellar reference through the field of a transit instrument whose plane of motion contains the bucket spin axis. This instrument would have to be computer-driven to anticipate the changing stellar "declination" between successive transits. Further, because of the Earth's proximity, any single stellar reference could be occulted by the Earth for as much as half of the Earth orbital period, and so several references would be required. A self-contained optical sensor would be ideal, but unknown tether torsion would make such an independent system difficult; high g-loadings make reliable gyroscopic sensing difficult. However, the last may have sufficient stability over several spin periods to be useful. If so, this scheme would undergo frequent updatings. The short-term stability of the bucket orbital period, namely tether revolution, is also passive and relies on the inherent stability of the orbital moment of momentum over an orbital period. The long-term stability could be mechanically tuned in a manner similar to the previous case. A pair of spider-masses performs a radial crawl along the tether, symmetric with respect to the CM, preserving the orbital moment of momentum. Sidereal sensing detects variations in the system's orbital period.

10. CONCLUSION

The technical feasibility of this scheme for the space manufacture of large high-quality telescopic mirrors, simple in principle, could be established by computer simulation. If feasible, the space shuttle provides an excellent platform from which to try a prototype. Other than the cost of freight to space, the process might be relatively inexpensive, especially when amortized over many mirrors. The important points are that the system can be assembled incrementally and that, once delivered to orbit, each increment may be repeatedly used.

Even if the optical quality turns out to be marginal, the process may still succeed by application of a computer-controlled polishing lap. Computer-controlled ion-scouring techniques may also become practical. Finally, the technology is available to enhance the performance of large mirrors by removing instrumental aberrations through digital deconvolution rather than by optical correction. The extremely accurate collimation of very stable fiber optic coherent light sources, together with CCD digital readout, where pixel resolution is aided by the large focal length of even the low f/ratio mirrors, will make automated image plane mapping a fast and accurate technique. Thereafter, digital images can be automatically deconvolved, and further processed, by on-line dedicated computer software.

It is doubtful that such extremely large single glass mirrors can be built on Earth, but even if they could, their transport into space would be impossible. Manufacture in situ is the solution to this dilemma. As a test case, preliminary work on a 1/10th-scale, 2-m mirror with a 10-km tether should pay dividends.

The presence of large light-gathering, high-resolution telescopes in space will revolutionize astronomy.

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This paper is dedicated to the memory of Walter B. Hamstrom, who would have greatly enjoyed the contemplation of this celestial bola.

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